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Dynamics of the geomagnetotail plasma sheet during storm time and non-storm time substorms

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Abstract We selected 40 substorm events from AMPTE/IRM satellite observations in the geomagnetotail at distances between 10 and 19 R_I ($1R_I$ = 6371 km) and separated storm time and non-storm time substorms and studied the dynamics of the near-earth geomagnetotail plasma sheet for the two types It was found that most of the signatures of the plasma sheet, typical for substorms, are strongly influenced by magnetic storm activity The field line curvature radius and chaos parameter in the plasma sheet are much more pronounced for substorms which occur during the main phase of magnetic storms than for non-storm substorms Moreover, only for storm time substorms, the specific entropy in the plasma sheet decreases during the expansion phase

Keywords Substorms plasma sheet temperature, plasma β-parameter

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1. Introduction

The behaviour of the geomagnetotail plasma sheet has been well explored by satellite observations. This domain of medium energy ($10^2 - 10^4$ eV) plasma is the site of various magnetospheric phenomena and hence its understanding is the key problem in most of the magnetospheric studies. The thermodynamics of the sheet appears slightly complicated due to the presence of different drift motions and various plasma instabilities. Also, the tail plasma sheet is a major sink for substorm energy and due to its dynamic structure and rapid changes during substorm intervals, case studies using satellite data have often lead to inconclusive results.

The plasma sheet energy density is suggested to be comparable with the magnetic field energy density [1]. The substorm time studies on the plasma sheet reveal that the near earth plasma sheet and the central plasma sheet are more affected by the substorm activity than the plasma sheet boundary layer [2]. The heating events in the plasma sheet which are less obvious, on closer examination revealed that they are associated with the expansive phase onset or a major intensification of a substorm. Other events which do not exhibit any dropout from the

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plasma sheet into the lobes are manifestations of a substorm injection [3]. The studies on the variation of the plasma sheet thermal conductivity and chaos parameter during substorm events were done recently [4]. The non-adiabatic behaviour of the substorm time plasma sheet at the geosynchronous orbit was also studied and established that the plasma sheet behaviour at the geosynchronous orbit was not described either by the adiabatic equation of state or by the constant magnetic moment equation [5].

A geomagnetic storm is usually defined as a large decrease in the horizontal component of geomagnetic field in middle or low latitudes, the decrease being mainly caused by a development of the equatorial ring current. A substorm is usually defined as a sequence of the processes in the polar region which is characterized by a sudden auroral brightening and subsequent intensification of auroral electrojects [6]. Geomagnetic storms and substorms are closely related, in the sense that both are developed when the interplanetary magnetic field (IMF) has a strong southward component. After a substorm onset, energetic particle injection is observed at geosynchronous orbit and the hourly Dst index becomes significant in magnitude [7]. So far, no storm, *ie,* no large Dst index development, has been reported without any substorm activity defined by sudden auroral electrojet intensification indicated by the AE indices. Russel *et al* [8] showed that the southward IMF is the controlling factor of Dst development rather than AE index. Gonzalez *et al* [9] showed that while no magnetic storms are observed in the absence of intense substorms, a substorm can occur independently of a magnetic storm. It is not clear, however, whether successive occurrence of intense substorm is a necessary condition for a magnetic storm. A better knowledge of the possible differences in the substorm associated changes in the magnetotail for high and low Dst values is crucial to understand the magnetotail behaviour associated with the solar wind– magnetosphere – ionosphere coupling during a substorm itself.

In the present paper, we have studied the average behaviour of the near-earth geomagnetotail plasma sheet during storm and non-storm times using some major substorm onsets and also performed a superposed epoch study to see whether there are any differences between the response of the near-earth tail plasma sheet for substorms that occur during the main phase of magnetic storms and for substorms without any accompanying storm activity.

2. Data and method

The tail survey data set from the IRM Satellite has been described earlier [10] and the information on the superposed epoch data set can be found in [11]. The plasma data were obtained using the plasma instrument on AMPTE / IRM Satellite [12]. For the eight months covered by IRM tail survey, Baumjohann *et al* [13] checked data from geosynchronous and near-geosynchronous satellites and the Kakioka ground magnetic station for substorm onset signatures and selected only those onsets where the signatures were well defined and also the AL index showed a clear substorm development. For multiple substorm onsets, the major onsets was taken. This way neglected smaller, localized onsets and obtained a list of 40 substorm onsets which can be classified as major global onsets. Their onset times and corresponding Dst values are given in Table 1.

We then used the Dst (geomagnetic storm index) index to distinguish between substorms occurred during times of magnetic storm activity and those which are not accompanied by storm intensifications. Here, we have chosen, somewhat arbitrarily, Dst $< -25\,nT$ for storm time substorms and Dst $>-25\,nT$ for non-storm substorms and found that 7 events are of the former

Table 1. Substorm onset times and corresponding Dst values

Substorm events		UT	Dst Value
1.	27.02.85	2204	– 16 nT
2	01.03.85	0232	- 27 nT
3.	01.03.85	0326	- 32 nT
4	22.03.85	1246	7 nT
5.	24.03.85	1148	2 nT
6.	25.03.85	1822	3 nT
7.	27.03.85	0607	– 18 nT
8.	27 03.85	0848	– 10 nT
9	28 03.85	0020	– 17 nT
10.	30.03.85	0002	– 3 nT
11.	08.04 85	2258	– 38 nT
12.	10.04.85	2130	– 12 nT
13.	11.04.85	0120	– 19nT
14.	16.04.85	0520	11 nT
15.	17.04.85	2345	– 6 nT
16.	19 04 85	0712	0 nT
17	19 04 85	0830	– 9 nT
18.	19 04 85	2208	- 49 nT
19.	11 05 85	0658	2 nT
20	13 05.85	0440	- 21 nT
21	15 05 85	2120	19 nT
22	16 05 85	1800	– 15 nT
23	18 05 85	1714	– 16 nT
24	13 03 86	0142	– 8 nT
25	14.03 86	2336	- 23 nT
26	15.03 86	0416	- 21 nT
27	21 03.86	2244	– 26 nT
28	08 04 86	2315	– 8 nT
29.	19 04 86	0058	3 nT
30	21 04 86	0030	– 1 nT
31	23 04.86	2302	– 5 nT
32.	25 04.86	0128	– 1 nT
33.	26.04.86	0138	– 8 nT
34.	04.05.86	2205	– 30 nT
35.	06.05.86	2349	– 71 nT
36.	01.06.86	2150	– 18 nT
37.	03.06 86	2019	– 8 nT
38.	05.06.86	2315	– 6 nT
39.	07.06.86	2124	– 19 nT
40.	09.06.86	1904	– 6 nT

type and 33 are of the later type. All the storm time substorms, which were studied, occurred during the storm main phase. Here, we are presenting the average behaviour of some plasma sheet parameters during the selected events separately for those onsets which occurred during the main phase of magnetic storm (Dst <–25 *nT*) and non-storm substorms (Dst >– 25 *nT*).

3. Results and discussions

Figure 1 shows the average behaviour of the plasma sheet temperature *T* during storm time (curve joining crosses) and non-storm time substorms (curve joining black dots) separately. The plasma sheet temperature is found to be increasing from substorm onset to the beginning of the recovery phase and this scenario is about the same for both types of substorms. The difference, however, between storm time and non-storm substorms lies in the average levels of the plasma sheet temperature before the onset, and thus also in the typical energy of plasma sheet particles during the expansion and recovery phases. From Figure 1, we can conclude that the heating of the plasma sheet seems to occur more rapidly during storm time expansion phases and it is very slow during the expansion phase of non-storm time substorms. This feature can be explained on the basis of the results obtained by [14] which reveals that during the course of a substorm, the plasma pressure in the plasma sheet increases and hence the energy density decreases. In order to maintain pressure balance, the total pressure in the plasma sheet must also increase. This is possible only by an adiabatic compression in the plasma sheet or plasma sheet heating. So there must be an increase of the plasma sheet temperatue for attaining the marginal stability state of the plasma sheet. This concept is in agreement with the loading–unloading model of substorms [15].

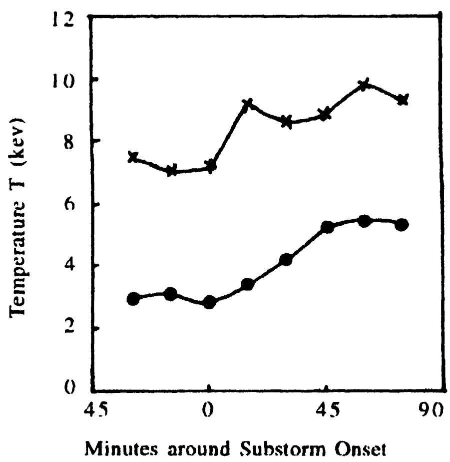

Figure 1. Average variation of the plasma sheet temperature *T* for storm time (curve joining crosses) and for non-storm substorms (curve joining black dots).

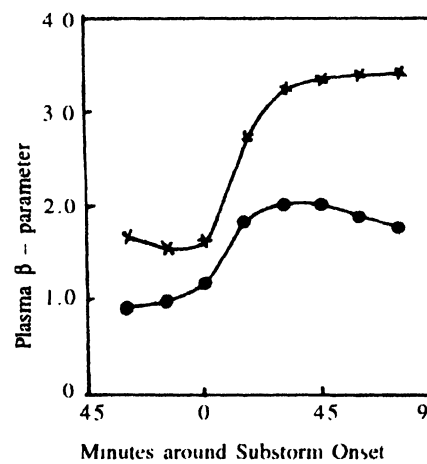

Figure 2. Average variation of plasma β-parameter for substorms whose onsets occurred at Dst < – 25 *nT* (curve joining crosses) and those at Dst > – 25 *nT* (curve joining black dots).

Figure 2 shows the more pronounced difference of the plasma β-parameter of the plasma sheet during the two types of substorms (curve joining crosses for storm time and curve joining black dots for non-storm substorms). It clearly illustrates that the variation of plasma β-parameter is about the same as that of plasma sheet temperature since the plasma β-parameter is a function of plasma sheet temperature and revealing that the increase of the plasma β-parameter in the plasma sheet occurs during the expansion phase. Also, the increase of the plasma β-parameter from substrom onset to the beginning of the recovery phase is about the same for both types of substorms. This results is in agreement with that of [14] which shows an increase of plasma β-parameter with the increase of plasma sheet temperature and geomagnetic activity index AE.

Figure 3 shows the behaviour of the plasma sheet specific entropy during the two types of substorms. The differnece between the two traces is most obvious. During non-storm substorms (curve joining crosses), the specific entropy of the plasma sheet does not change in any systematic way. In fact, one may even say that the plasma sheet is not affected at all by those substorms. On the other hand, the plasma sheet specific entropy changes quite drastically during the expansion phase of storm time substorms (curve joining black dots). It starts from a somewhat higher level, but even more rapidly, it drops to about half of its pre-onset values during the expansion phase. Note that the decrease of the specific entropy before the storm time substorm onset is more likely an artifact caused by uneven data coverage. The specific entropy studies in the plasma sheet during some selected substorm events for different fluctuation levels of the ULF wave passing through the resonance layer of the plasma sheet was made [16] and revealed that the specific entropy was found to be increasing with the amplitude of oscillation of the ULF wave and also with plasma β-parameter

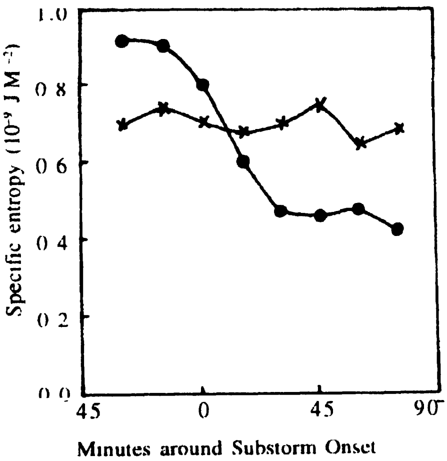

Figure 3. Average variation of the plasma sheet specific entropy during storm time (curve joining black dots) and non-storm substorms (curve joining crosses)

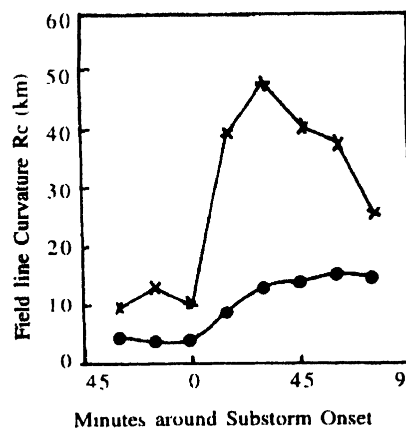

Figure 4. Average variation of field line curvature radius R_c during storm time (curve joining crosses) and non-storm substorms (curve joining black dots)

Figure 4 shows the temporal development of the field line curvature radius R_c in the plasma sheet separately for storm time (curve joining crosses) and non-storm time substorm events (curve joining black dots). The difference between the two types of substorms become very clear in Figure 4. During substorms that are not accompanied by magnetic storm activity, the field line curvature radius appears to be very gradual, reaching its highest, value only during the recovery phase. Moreover, the field line curvature radius is not very pronounced, with an average maximum value of 500 kms. On the other hand, for substorms which occur during the storm main phase, the curvature radius of field lines in the plasma sheet reaches its maximum value.

Figure 5 shows the variation of the chaos parameter K ($K = R_c / r$), where r is the ion gyro radius) in the plasma sheet for the two types of substorms (curve joining black dots for storm time and curve joining crosses for non-storm time substorms). Since r is taken as a constant, the variation of K is constructed the same way as that of R_c. Here also the difference between the two types of substorms becomes very clear from the variation of K. Bindu *et al* [17] showed that as the auroral electrojet index AE increases, R_c and K increases gradually and reaches a maximum value for maximum AE. Since K depends on the field intensity B in the plasma sheet and mass of the moving particle, for a constant mass of the moving particle, R_c and B are large during strong storms and so there is an increase of K with AE index. Since K and R_c are playing important roles in instabilities in the plasma sheet associated with geomagnetic activity, we can assign the instability changes during the two types of substorms.

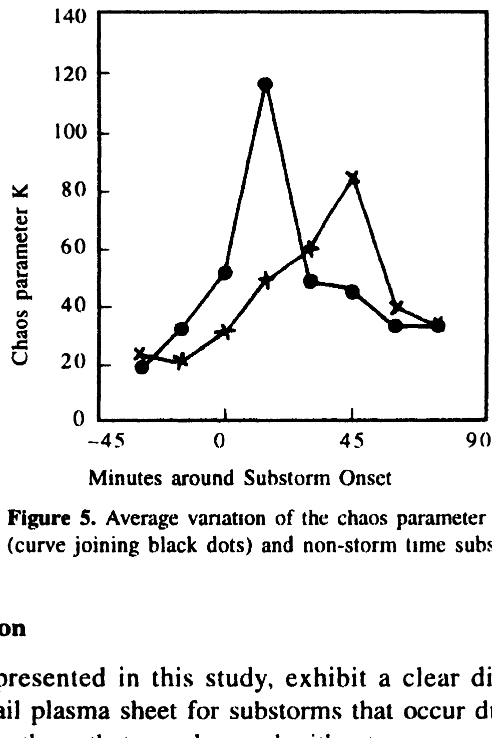

Figure 5. Average variation of the chaos parameter K in the plasma sheet during storm time (curve joining black dots) and non-storm time substorms (curve joining crosses)

4. Conclusion

The results presented in this study, exhibit a clear difference in the dynamics of the geomagnetotail plasma sheet for substorms that occur during the main phase of magnetic storms and for those that are observed without accompanying magnetic storm activity. The study indicates that even though the ionospheric signatures are the same for the both types of substorms, there may be two qualitatively different types of substorms, which are dominated by two different physical processes in the magnetosphere. If this is really the case, it would resolve some apparently contradictory results from earlier substorm studies. Our present study also shows that atleast a first step in this direction might be to look into magnetospheric substorm signatures in different regions of the tail, based on all onsets defined by ionospheric data from auroral latitude but at the same time taking into account the state of the solar wind and the IMF.

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